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# Influencing Factors and Workpiece's Microstructure in laser-assisted Milling of Titanium

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## Abstract

Today's lightweight components have to withstand increasing mechanical and thermal loads. Therefore, advanced materials substitute conventional materials like steel or aluminum alloys. Using these high-performance materials the associated costs become prohibitively high. This paper presents the newest fundamental investigations on the hybrid process 'laser-assisted milling' which is an innovative technique to process such materials. The focus is on the validation of a numerical database for a CAD/CAM process control unit which is calculated by using simulation. Prior to that, the influencing factors on a laser-assisted milling process are systematically investigated using Design of Experiments (DoE) to identify the main influencing parameters coming from the laser and the milling operation.

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**Keywords:** Milling; Laser-assisted; Titanium; CAD/CAM; Design of Experiments

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## 1. Motivation

The distinctive trend to lightweight constructions is one of the central challenges for engineering scientific research. This trend is encouraged by the shortage of the global resources and the resulting price development of raw materials and energy. A modern concept for lightweight construction calls for new and advanced materials as well as the development of new production techniques. For high performance components advanced materials, like titanium alloys, substitute conventional steel materials or aluminum alloys. The usage of titanium is, however, strongly limited by its higher cost relative to competing materials. The processing also causes problems associated with the production, e.g. high tool wear or low material removal rates. Nevertheless, the newest generation of aircrafts consists of up to 20 % titanium

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alloys. The high electric potential difference between carbon composites, another upcoming lightweight material, and aluminum alloys results in a severe galvanic corrosion. This encourages the usage of titanium alloys in combination with carbon composites, due to the minor electric potential difference. The similar characteristic of the heat expansion is advantageous, too. Compared to other materials titanium alloys bring together a high specific strength and good corrosion resistance. They also withstand working temperatures of up to 500 °C without losing their mechanical strength [1]. Therefore, titanium is the ideal lightweight material. But the machining process is a very cost intensive manufacturing step as high production times and costs respectively complicate an economic machining process [2].

For some integral construction parts material removal rates of up to 95 % are required [3]. A high amount of the raw material, which was produced with high energy input, is formed to chips and has to be recycled without a production-related benefit. Therefore, machining is more and more scrutinized because of its energy and environmental impact. New near net-shape techniques, like casting, forging or additive manufacturing, are still under investigation. Nevertheless, machining is one of the most established processing techniques, which has already been investigated in detail for years. These investigations provide the applicability of today's capable and robust machining processes. The generated process knowledge ensures the desired material properties after the production process and thus the desired attributes and quality of the residual part. Despite the described situation there will be no alternative to machining of advanced materials in the future. To meet the market requirements for a flexible as well as capable and robust manufacturing process, innovative processing techniques are needed.

Hot machining represents such a technique to enhance machinability. The general principle is to heat and thereby soften the material before machining. Due to the induced heat the cutting forces and therefore the mechanical and thermal load on the tool can be reduced. This effect enables an increase of the material removal rate and therefore a reduction of the processing time. Alternatively, the tool life is extended at a constant material removal rate. The use of a laser beam to locally pre-heat the material in front of the tool is one of the most innovative approaches for hot machining, see Fig. 1.

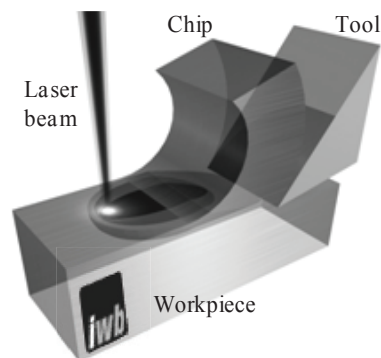


Fig. 1. Principle of locally heating the material in front of the tool in laser-assisted machining

## 2. State of the Art and preliminary Work

In spite of the high potential of the processing technique, laser-assisted milling is not yet deployed for industrial applications. Former investigations of laser-assisted milling for different materials, like aluminum, steel, inconel, silicium nitride or titanium (e.g. [4–11]) supply the proof of principle. But these researches revealed two major problem areas which restrict an economic realization of the process: *Process reliability* and *systems technology*. The missing understanding of the physical effects and their influences on the process results in a possible damage of the material's microstructure caused by a thermal overload. Additional high efforts in the systems design of the laser integration are necessary, due to the highly dynamic movement of the milling tool. For these reasons, the hybrid process has to be systematically investigated and a machine concept, which provides a reliable and economic machining strategy, has to be developed. During the research project "Laser-Assisted Milling of advanced Materials" the mechanisms of the process were investigated using experimental methods and simulation [12, 13]. Also a prototype of a machine for laser-assisted milling, which is characterized by application-related and cost-effective engineering using a modular design of the laser beam integration, was developed [14, 15]. Fig. 2 illustrates the system and the components of the modular and retrofit laser integration. A torque motor is coaxially mounted at the spindle unit to position the laser spot directly in front of the tool. The laser beam coming from the laser optics is deflected into the machining zone by a mirror.

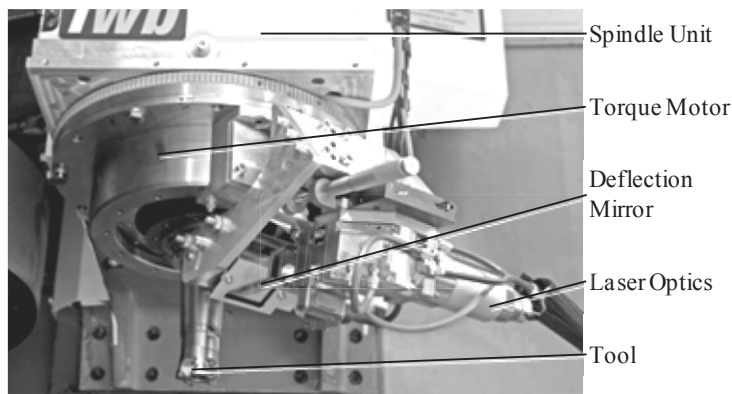


Fig. 2. Modular and retrofit laser integration mounted in a conventional milling machine

Finally, to realize a capable process using the developed laser integration the combined influencing factors of the milling and the laser operation have to be identified. Also a database of parameters is needed to control the laser parameters subject to the current milling situation using CAD/CAM. E.g., for a given milling situation (depth of cut and feed rate) the laser power has to be adjusted to prevent the remaining workpiece from a thermal overload. Otherwise the thermal damage of the workpiece's material causes a reduced mechanical strength and increased susceptibility to cracking.

### 3. Experiments

#### 3.1. Experimental Setup

A laser-assisted milling operation is influenced by several process parameters of both operations; milling and laser material processing. The main reason for the limited economic feasibility of milling of titanium alloys is the high production time because of the high mechanical load on the milling tool and the resulting high tool wear. Therefore, the cutting forces are within the scope of the following investigations. In Fig. 3 the influencing parameters are listed and the figure illustrates them for laser-assisted milling. For all investigations the laser spot was located at the edge of the workpiece to reduce the strength of the material at the location where the maximum force and therefore the maximum tool wear occurs. All experiments were conducted on a MAS milling machine type NCV 750. The milling tool was a Pokolm coated carbide metal high-feed cutter of type Quadworx, which is approved for extremely high feed rates at moderate depths of cut. The cutting forces were measured with a 3-component-dynamometer Kistler 9257A. The laser was an Yb-fiber-laser with a wavelength of  $\lambda_{yb} = 1070$  nm.

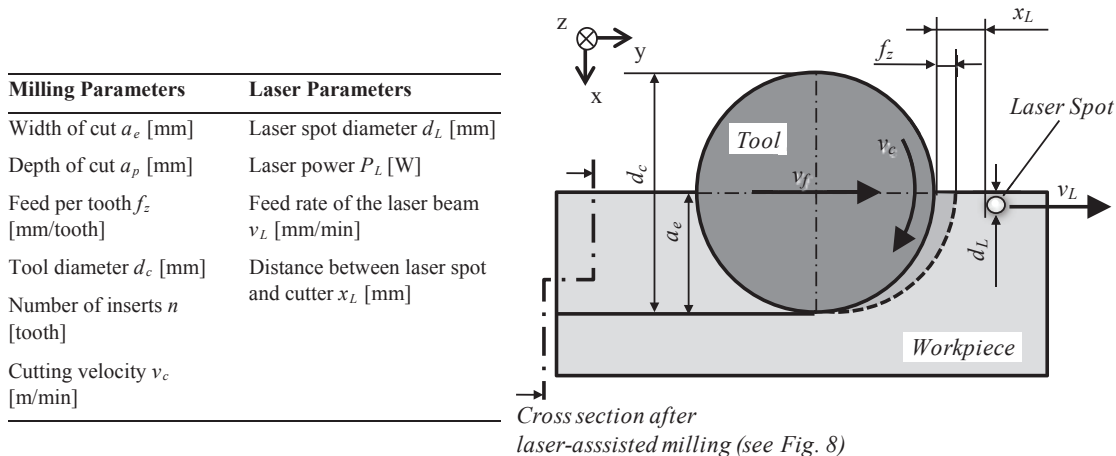


Fig. 3. (a) experimental parameters; (b) their illustration for the investigation on laser-assisted milling, top view

Since the number of variables in the hybrid process is high, Design of Experiments (DoE) was used for the investigation of the influence and the interaction of each parameter. The following investigations focus on the cutting forces and do not consider a possible change of the microstructure by thermal overload. The microstructure is taken into account in the following section 5. This approach allows for an independent determination of the possible range of the cutting force reduction. The transient temperature field within the workpiece was investigated using simulation methods, see [13]. Former investigations on conventional milling showed that the main influencing parameters on the cutting force are the depth of cut  $a_p$ , the feed rate  $v_f$  and the width of cut  $a_e$  [17]. The feed rate is calculated by equation (1). As the laser unit is fixed to the spindle unit, the feed rate of the laser beam  $v_L$  is the same as the feed rate of the milling tool  $v_f$ .

$$v_f = v_L = (f_z \cdot v_c \cdot n) / (d_c \cdot \pi). \quad (1)$$

### 3.2. Design of Experiments

Following the available investigations in literature, compare [4-11], the laser parameter laser power  $P_L$  and the laser spot diameter  $d_L$  were also chosen for DoE investigations. In addition, the distance between the laser spot and the cutter  $x_L$  is considered. Altogether six parameters are investigated. The method Central Composite Design (CCD) was chosen to determine their influence on the cutting forces in the three spatial directions  $F_{x/y/z}$ . The experimental design consists of a full factorial square and a centered star; see Fig. 4 for two dimensions. The experimental design consisting of six influencing factors and their factor levels for CCD is summarized in Table 1. The software Visual-XSel 11.0 was used for the design and the analysis of the experiments. Based on the measured maximum forces  $F_{x/y/z,max}$  a regression model for each spatial direction, which allows an analytical prediction of the maximum force within the investigated range of the influencing parameters, was determined. The statistical degree of the approximation of the regression model and the measured data is specified by the coefficient of determination  $R^2$ .  $R^2 = 1$  indicates that the regression model perfectly fits. Here, it was determined to be  $R^2 = 0.970 \dots 0.987$ . Therefore, the model provides a good approximation of the experiments.

As the reduction of the cutting force due to laser assistance is calculated as the difference between a conventional and a laser-assisted milling operation, two measured data, which have to be subtracted, are required. Therefore, two different regression models were determined: *Model 1* includes all six influencing parameters, *model 2* only includes the three milling parameters  $a_p$ ,  $f_z$  and  $a_e$ . The difference between these two models allows the analytical determination of the reduction of the force  $\Delta F$ .

Table 1. Experimental design consisting of the influencing factors and the factor levels for CCD ( $\alpha = 2.0$ )

	Factor level				
	$-\alpha$	$-1$	$0$	$1$	$\alpha$
$a_p$ [mm]	0.1	0.3	0.5	0.7	0.9
$f_z$ [mm/tooth]	0.2	0.5	0.8	1.1	1.4
$a_e$ [mm]	8.0	14.0	20.0	26.0	32.0
$P_L$ [W]	100	350	600	850	1100
$x_L$ [mm]	1.0	2.0	3.0	4.0	5.0
$d_L$ [mm]	1.7	2.1	2.5	2.9	3.3

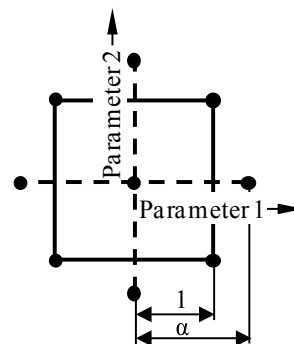


Fig. 4. 2-dimensional experimental design (CCD)

### 3.3. Regression Model

The general equation of the quadratic *model 1* is given below, see equation (2). The prediction of the process forces  $F_x$ ,  $F_y$  and  $F_z$  within the investigated parameter range can be calculated with the determined coefficients  $K$  of the regression model, see Table 2.

$$F_j = K_0 + K_1 \cdot a_p + K_2 \cdot a_e + K_3 \cdot f_z + K_4 \cdot P_L + K_5 \cdot x_L + K_6 \cdot d_L + K_7 \cdot a_p \cdot f_z + K_8 \cdot a_p \cdot a_e + K_9 \cdot a_p \cdot P_L + K_{10} \cdot a_p \cdot x_L + K_{11} \cdot a_p \cdot d_L + K_{12} \cdot f_z \cdot a_e + K_{13} \cdot f_z \cdot P_L + K_{14} \cdot f_z \cdot d_L + K_{15} \cdot a_e \cdot P_L + K_{16} \cdot a_e \cdot x_L + K_{17} \cdot P_L \cdot x_L + K_{18} \cdot a_p^2 + K_{19} \cdot f_z^2 + K_{20} \cdot a_e^2 + K_{21} \cdot P_L^2 + K_{22} \cdot x_L^2 + K_{23} \cdot d_L^2 \quad (2)$$

With the spatial direction  $j = [x; y; z]$  and the coefficients  $K_{0...23}$  from Table 2

Table 2. Coefficients  $K_{0...23}$  of the quadratic regression *model 1* to calculate the process forces  $F_x$ ,  $F_y$  and  $F_z$

$j$	$K_0$	$K_1$	$K_2$	$K_3$	$K_4$	$K_5$	$K_6$	$K_7$	$K_8$	$K_9$	$K_{10}$	$K_{11}$
$x$	1172	-453	41	-436	0.4	-19	-974	1626	94	-0.8	0	0
$y$	-714	1457	45	598	0.1	-23	0	730	-14	-0.2	0	0
$z$	-3315	5418	208	2120	-0.5	25	61	0	143	0	-152	0

$j$	$K_{12}$	$K_{13}$	$K_{14}$	$K_{15}$	$K_{16}$	$K_{17}$	$K_{18}$	$K_{19}$	$K_{20}$	$K_{21}$	$K_{22}$	$K_{23}$
$x$	23	0.4	0	0.01	0	0.04	-725	0	-1.9	0	0	189
$y$	0	0	0	0	1.9	-0.03	-562	-276	-1.1	0	0	0
$z$	23	0	0	0.01	3.2	0	-5034	-1114	-6.5	0	0	0

As is to be expected, the milling parameters  $a_p$ ,  $f_z$  and  $a_e$  have the strongest influence on the cutting forces of a laser-assisted milling operation. The additional laser parameters have a lower degree of influence on the maximum force. Laser-assisted milling aims on the improvement of the technology ‘conventional milling’ by the help of laser radiation. Therefore, for investigation on laser-assisted milling the laser parameters are within the scope of interest. Fig. 5 shows the process forces of the three spatial directions, which were calculated by using the regression model, and their confidence interval for a probability of 95 % under variation of the three laser parameters. Also the standard deviation  $\sigma_j$  for each spatial direction is illustrated. Within the investigated range the laser power  $P_L$  has the strongest influence on the maximum forces of all directions. A general trend is: The higher the laser power, the lower the process force. A distinctive trend can also be observed for the forces  $F_x$  and  $F_z$  and a variation of the spot diameter  $d_L$ . For  $F_x$  a minimum is located at  $d_L = 2.65$  mm. A minimized distance between the cutter and the laser spot  $x_L$  seems to be advantageous. For the other combinations of the force in the spatial direction and the influencing factor there are no significant effects, as the total effects are within the standard deviation and the confidence interval respectively.

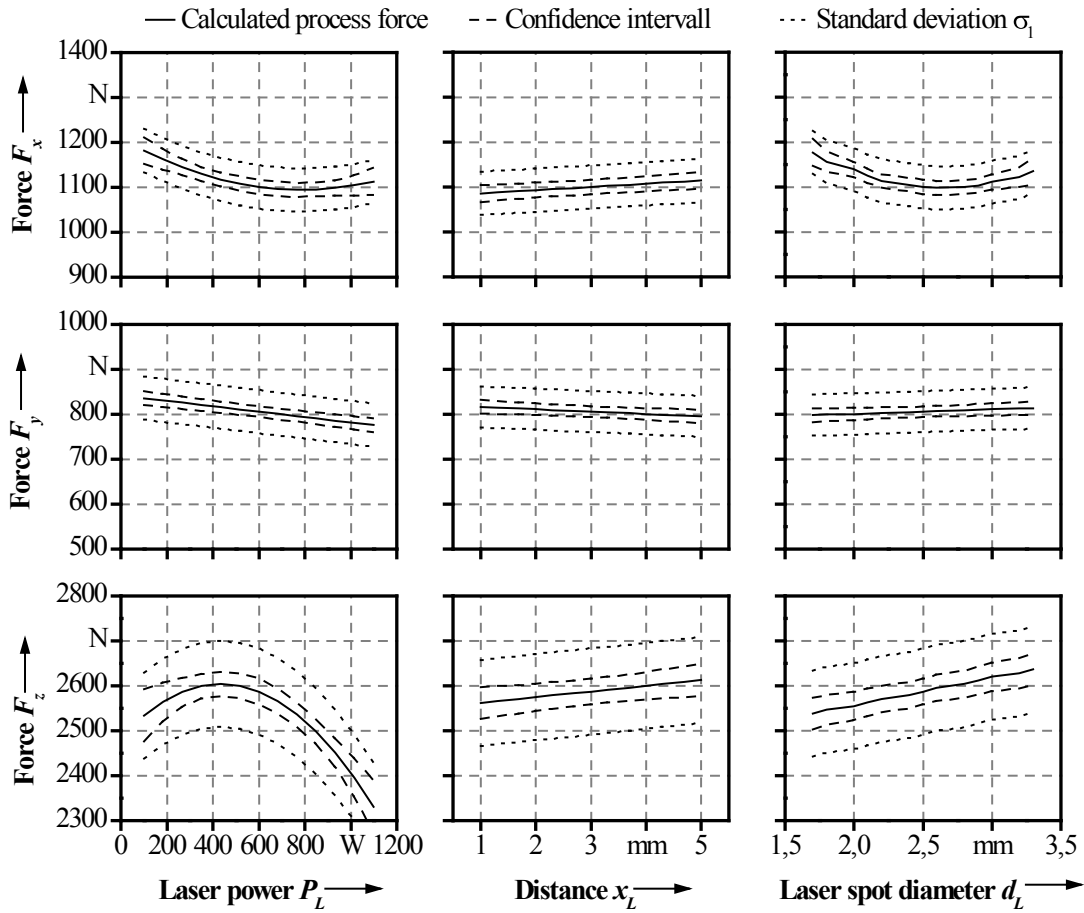


Fig. 5. Calculated process forces  $F_x$ ,  $F_y$  and  $F_z$  with confidence intervals and standard deviation  $\sigma_1$  under variation of the laser power  $P_L$ , the distance between the laser spot and the cutter  $x_L$  and the laser spot diameter  $d_L$  ( $a_p = 0.5$  mm,  $a_e = 20$  mm,  $f_z = 0.8$  mm/tooth)

As described above, the reduction of the force  $\Delta F$  is calculated from the difference between a conventional and a laser-assisted process. Fig. 5 indicates that the laser power  $P_L$  is the main influencing parameter on the resulting process forces. Fig. 6 exemplarily shows the reduction of the maximum forces for laser-assisted milling under variation of the laser power  $P_L$ . The reduction shown in Fig. 6 was calculated for milling parameters:  $a_p = 0.7$  mm,  $f_z = 1.2$  mm/tooth,  $a_e = 20$  mm,  $d_L = 2.5$  mm and  $x_L = 3.0$  mm. There is no confidence interval for the reduction of the force because the reduction is a calculated value from two regression models. Therefore, the confidence interval is replaced by the accumulated standard deviation  $\sigma_{12}$ . The standard deviation  $\sigma_{12}$  is calculated out of the standard deviations  $\sigma_1$  and  $\sigma_2$  of *model 1* and *model 2*, see equation (3) [18]. As illustrated in Fig. 5 the range of the standard deviation also covers the range of the confidence interval.

$$\sigma_{12} = \sqrt{\sigma_1^2 + \sigma_2^2} \quad (3)$$

The force in  $x$ -direction is significantly reduced due to the laser assistance. For a reduction of the force in  $z$ -direction higher laser powers are needed. Due to the location of the laser spot at the edge of the workpiece to irradiate the location where the maximum force occurs, there is only a slight reduction of the force in  $y$ -direction.

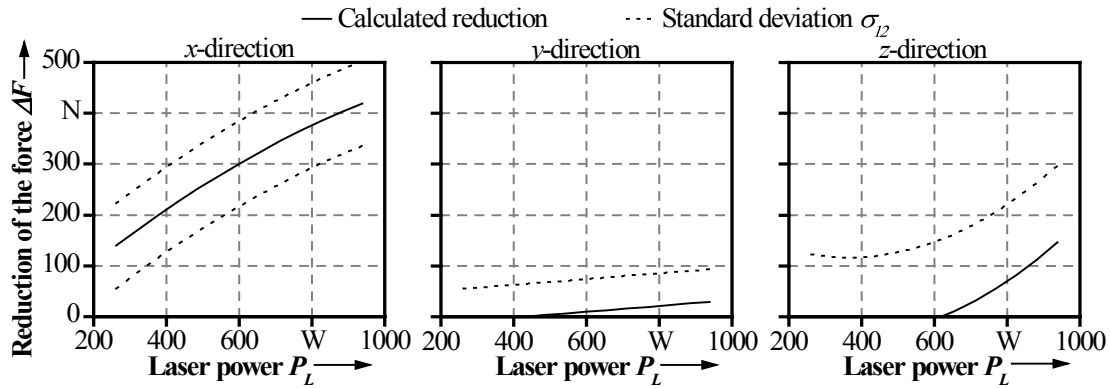


Fig. 6. Reduction of the maximum process forces  $\Delta F_x$ ,  $\Delta F_y$  and  $\Delta F_z$  versus the applied laser power  $P_L$  and determined standard deviation  $\sigma_{l2}$  ( $a_p = 0.7$  mm,  $f_z = 1.2$  mm/tooth,  $a_e = 21$  mm,  $d_L = 2.5$  mm,  $x_L = 3.0$  mm)

### 3.4. Midterm Conclusion from DoE

The investigations described above provide a regression model to predict the process forces in laser-assisted milling, see equation (2) and Table 2. Also the determination of the reduction of the process forces is exemplarily shown using CCD. From the DoE investigations two trends have been observed: The laser power  $P_L$  should be maximized and the distance between the cutter and the laser spot  $x_L$  should be minimized to minimize the process forces in laser-assisted milling. Also a theoretical optimum for the laser spot diameter at  $d_L = 2.65$  mm was determined for the investigated range of the parameters. These summarized results are considered for the subsequent approach.

## 4. Numerical Database from Simulation

### 4.1. Simulation Model

For a laser-assisted process it is essential to know the temperature inside the material after laser radiation of the workpiece. There are no nondestructive experimental methods to investigate the temperature field inside the workpiece. To determine the internal temperature, the detour using an experimentally calibrated simulation was made. The temperature on the workpiece's surface after laser radiation of the workpiece was measured by using thermocouples or a thermal imaging camera [16]. The measurement of the geometry of the heat affected zone (HAZ) allows for an indirect but destructive indication of the temperature. For investigations on the temperature field inside a workpiece a simulation model was built up. The approach and the setting are already described in former publications, see [13, 16]. The measurements of the surface temperature were used to calibrate the simulation model. A comparison of the calculated temperature and the isothermal lines in the simulation respectively and the measured geometry of the HAZ validated the simulation model. In the simulation model all process parameters coming from the laser process ( $P_L$ ,  $d_L$ ,  $x_L$ ,  $v_L$ ) can be varied and the resulting temperature can



be determined without additional experimental efforts. Following the investigations which are already presented in [12], the distance between the laser spot and the cutter is set to  $x_L = 1.5$  mm for subsequent investigations.

#### 4.2. Setup of the numerical database

A thermal restriction of a laser-assisted process is, that the remaining workpiece must not be overheated to avoid irreversible microstructural changes (starting at the titanium martensite start temperature  $T_{MS} = 800$  °C). However, in the depth of cut  $a_p$  the temperature has to exceed the softening temperature of 400... 450 °C. Hence, the maximum admissible temperature in the depth of cut ranges from 450 °C to 800 °C. As microstructural changes are depending on the temperature, the temperature inside the workpiece during a laser-assisted process has to be well known. The three laser parameters laser power  $P_L$ , laser feed rate  $v_L$  and laser spot diameter  $d_L$  mainly influence the temperature. The laser spot diameter is fixed for the developed laser integration and the laser feed rate  $v_L$  is depending on a current milling operation  $v_f$ . Thus, the parameter laser power  $P_L$  has to be adapted for every single milling situation (depth of cut  $a_p$  and feed rate  $v_f$ ) to avoid an overheating of the material. For an industrial application it is essential that the laser power can be controlled automatically depending on the milling situation. It is state of the art that a CAD/CAM process control unit generates an NC code for a milling operation. An upgraded CAD/CAM unit additionally adapts the laser power and includes the position data of the laser spot. For this reason, the dependency of the laser power  $P_L$  and the feed rate  $v_f$  and the depth of cut  $a_p$  during milling is stored in a database in the background of a CAD/CAM unit.

Based on the investigations described above such a database was created using the described simulation model. The database consists of the laser power  $P_L$  in correlation with the milling parameters  $a_p$  und  $v_f$ . The resulting temperature after laser radiation was calculated for varied laser powers and feed rates. The approach to determine the necessary laser power to soften the material without a thermal damage is exemplarily shown in Fig. 7 for two different depths  $z$ . To reach a temperature of  $T_{max} = T_{MS} = 800$ °C in a depth of  $z = 0.5$  mm (which is also the depth of cut  $a_p$ ) a laser power of  $P_{L,0.5} = 439$  W has to be applied for the given feed rate. For a depth of  $z = 0.9$  mm a laser power of  $P_{L,0.9} = 726$  W is needed. The simulation allows for the determination of the necessary laser power  $P_L$  for every combination of the feed rate  $v_f$  and depth of cut  $a_p = z$ .

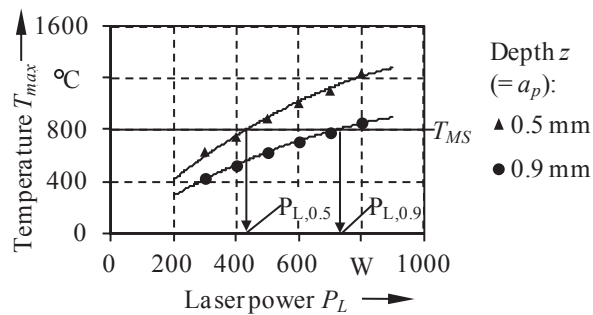


Fig. 7. Maximum temperature  $T_{max}$  for two different depths  $z$  (0.5 mm and 0.9 mm) versus the laser power  $P_L$  calculated in simulation and determination of the necessary laser power for laser-assisted milling ( $v_L = 1.6$  m/min,  $d_L = 2.65$  mm, TiAl6V4)

#### 4.3. Experimental Validation

The numerical database was validated using cross sections of the workpiece after laser-assisted milling. For the conducted experiments the experimental setup, which is described in section 3 and 4, was used. No microstructural changes may occur for capable parameters. Five cross sections of the workpiece after laser-assisted milling with different parameters are exemplarily shown in Fig. 8. The central parameter setting consists of the adapted laser power  $P_{L,0.5}$  from simulation for the given feed rate and depth of cut of  $a_p = 0.5$  mm. The experimental design is a centered star with a variation of the energy input per unit length  $S_L$ .  $S_L$  is a characteristic parameter for laser material processing and is given by equation (4).

$$S_L = P_L / v_L \quad (4)$$

The cross section shown in the center of Fig. 8 is a workpiece of titanium TiAl6V4 which was milled using the adapted laser parameters from the numerical database. No formation of a heat affected zone (HAZ) and therefore no thermal damage by microstructural changes can be observed. For an increase of the energy input per unit length  $S_L$  obviously a heat affected zone (HAZ) can be detected, see Fig. 8b/c. In contrast, the material shown in Fig. 8d/e was milled with decreased  $S_L$  and no HAZ was detected. These experimental results confirm the prediction from simulation. It is thereby demonstrated that a simulation model can be used to setup a capable numerical database for a CAD/CAM system to automatically adjust the process parameters during the milling process. For such an application, a database calculated from simulation, e.g. a matrix of process parameters, is needed in the background of a CAD/CAM unit.

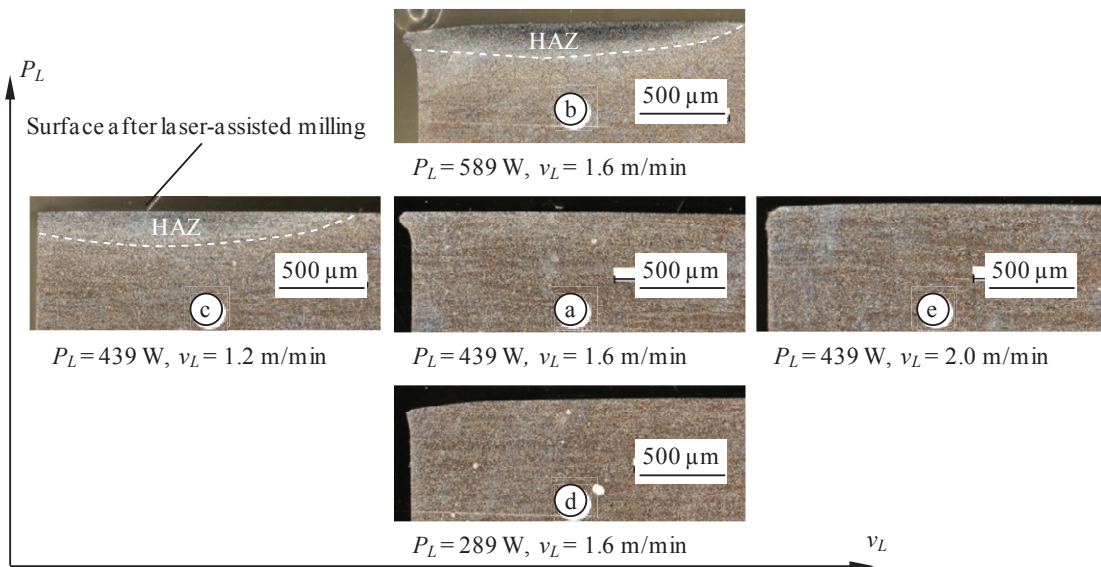


Fig. 8. Cross section polishes of workpieces after laser-assisted milling (see Fig. 3) applying the adapted laser power from the numerical database and varied energy input per unit length  $S_L$  ( $a_p = 0.5$  mm,  $a_e = 21$  mm,  $d_L = 2.65$  mm,  $x_L = 2$  mm, TiAl6V4)

## 5. Summary and Future Work

The presented work shows an approach to identify the main influencing parameters on a laser-assisted milling operation using DoE with a CCD. The achieved knowledge is necessary to understand the interaction of the process parameters with each other and the dependency of the cutting force as well as the resulting microstructure. Also a numerical database consisting of laser and milling parameters, which is used for a CAD/CAM process control unit, was validated. It is shown, that due to the application of the adapted laser parameters a change in the microstructure by thermal overload can be prevented. Therefore, a simulation model can be used to reduce experimental efforts and to setup a numerical database for a CAD/CAM process control unit in laser-assisted milling. The process parameters can automatically be adjusted during a process using such a matrix of milling parameters in a CAD/CAM environment.

The long term objective of the research group is to roll out an application related as well as economic system technology for laser-assisted milling. The next steps will be to optimize the laser integration system and the milling strategy to increase the efficiency of the process.

## Acknowledgement

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## References

- [1] R. Boyer, G. Welsch, E.W. Collings (Eds.): *Materials properties handbook: Titanium alloys*, 4<sup>th</sup> ed., ASM International, Materials Park, Ohio, 2007.
- [2] E.O. Ezugwu, Z.M. Wang: *Titanium alloys and their machinability - a review*, In: *Journal of Materials Processing Technology* 68 (1997), pp. 262–274.
- [3] R. Schnadt-Kirschner: *Praktische Aspekte der Zerspanung von Flugzeugintegralbauteilen aus Aluminium- und Titanlegierungen*, In: 31. Fachgespräch zwischen Hochschule und Industrie - Bohren und Fräsen im modernen Produktionsprozess, 1997, pp. 31–41.
- [4] U.B. Klossowski: *Laserunterstütztes Fräsen von TiAl6V4*. Diss. RWTH Aachen (Berichte aus der Produktionstechnik 27/99), Shaker, Aachen, 1999.
- [5] Y. Tian, B. Wu, M. Anderson, Y.C. Shin: *Laser-assisted Milling of Silicon Nitride Ceramics and Inconel 718*, In: *Journal of Manufacturing Science and Engineering* 1230 (2008), pp. 130103.1-9.
- [6] Y. Jeon, F. Pfefferkorn: *Effect of Laser Preheating the workpiece on Micro end Milling of Metals*, In: *Journal of Manufacturing Science and Engineering* 130 (2008), pp. 011004.1-9.
- [7] T. Furumoto, T. Ueda, T. Osaka, A. Yassin, A. Hosokawa, R. Tanaka: *Study on Laser Assisted Milling of Ferrous Based Consolidated Material*, In: *Journal of Mechanical Science and Technology* (2009), pp. 127-130.
- [8] B. Yang: *Experimental and numerical investigation of laser assisted milling of silicon nitride*. PhD Thesis KSU, Manhattan, Kansas, 2009.
- [9] C.J. Rosen: *Laserunterstützte Fräsbearbeitung hochfester Werkstoffe*. Diss. RWTH Aachen (Ergebnisse aus der Produktionstechnik 01/12), Apprimus, Aachen, 2012.

- [10] C. Brecher, M. Emonts, C. J. Rosen, J.-P. Hermani, "Laser-assisted Milling of Difficult-to-machine Materials," in 9<sup>th</sup> International Conference on High Speed Machining: Innovation in Machining, 2012, pp. 95–98.
- [11] C. Brecher, M. Emonts, C. J. Rosen, J.-P. Hermani, "Laserunterstützte Fräsbearbeitung," In: wt Werkstattstechnik online, vol. 102, no. 6, 2012, pp. 353–356.
- [12] R. Wiedenmann, M. Langhorst, M.F. Zaeh: Computerized Optimization of the Process Parameters in Laser-Assisted Milling, In: M. Schmidt, M.F. Zaeh, T. Graf, A. Ostendorf (Eds.), Lasers in Manufacturing 2011: LiM 2011, Elsevier, Amsterdam, 2011, pp. 607–616.
- [13] M.F. Zaeh, R. Wiedenmann: Prozessuntersuchung zum laserunterstützten Fräsen von Titanlegierungen, In: wt Werkstattstechnik online, vol. 101, no. 7/8, 2011, pp. 482–486.
- [14] D. Belforte: Laser-assisted milling of titanium alloys, In: Industrial Laser Solutions 26 (2011), p. 5.
- [15] M.F. Záh, R. Wiedenmann: Systemtechnik zum laserunterstützten Fräsen: Anwenderorientierung und Wirtschaftlichkeit durch modulare Laserintegration, In: ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb 106 (2011), pp. 506–509.
- [16] M. F. Zaeh; R. Wiedenmann; R. Daub: A Thermal Simulation Model for Laser-Assisted Milling, In: Laser Assisted Net Shape Engineering (LANE): 6<sup>th</sup> International Conference, 2010, pp. 353–362.
- [17] R. Wiedenmann, M.F. Zaeh: Fundamental Investigations on conventional Milling in the Overall Context of a laser-assisted Process, *submitted and accepted for publication*: In: Proceedings of MATAR 2012 and MM Science Journal, 2012
- [18] L. Råde, B. Westergren, P. Vachenaer: Springers mathematische Formeln: Taschenbuch für Ingenieure, Naturwissenschaftler, Informatiker, Wirtschaftswissenschaftler, 3<sup>rd</sup> Ed., Berlin, Springer, 1997.